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Abstract

We currently are studying an advanced space Very Long Baseline Interferometry (VLBI) mission called ARISE (Advanced Radio Interferometry between Space and Earth). One or two spacecraft in Earth orbit would form interferometers on baselines to many ground radio telescopes, thus synthesizing a highly sensitive radio telescope with an effective size larger than the Earth's diameter. ARISE would be a much more sensitive successor to the first generation space VLBI missions, VSOP and RadioAstron, which will fly in the late 1990s. A critical component of ARISE must be a large antenna in orbit, with a diameter of 25–30 meters, that is capable of operating with high aperture efficiency at frequencies ranging from 5 GHz to 43 GHz; operation (perhaps with lower aperture efficiency) at 60 GHz and 86 GHz is highly desirable. The leading candidate for an inexpensive, reliably deployable telescope meeting these requirements is an inflatable antenna using the technology to be demonstrated in a flight experiment in 1996. This paper reviews the characteristics of present and proposed space VLBI missions, then describes the primary requirements that the ARISE mission places on such an inflatable antenna.

Background

Astronomers have been engaged in a quest for higher angular resolution for many years, to further our understanding of celestial objects. Over the last 40 years, they routinely have used the method of radio interferornetry in order to achieve improved resolution at radio frequencies. This technique involves using two or more separated radio telescopes that simultaneously observe the same radio source. By receiving signals at arrays of telescopes and cross-correlating them, astronomers can synthesize a large radio telescope whose diameter (for the purposes of angular resolution) is equal to the size of the telescope array. The basic element in such an array is the two-element interferometer; the results of an experiment involving N participating telescopes effectively come from combining the data of all the $N(N-1)/2$ interferometers that can be formed from these telescopes. For a maximum telescope separation of a few kilometers, the effective resolution is on the order of an arcsecond, similar to that of optical telescopes.

Since 1967, the technique of Very Long Baseline Interferometry (VLBI) has been used to further enhance the resolution available on astronomical objects.[1-3] In this technique, telescopes separated by distances equal to large fractions of the Earth's diameter are employed. These telescopes, which use independent clocks, digitize and record data received in a moderately large bandwidth. The data are later brought together for cross-correlation at a central processing facility. Resolution on the order of a milliarcsecond (0,001 arcsecond) is routinely achieved. With this resolution, which is 50-100 times better than that available with the Hubble Space Telescope, astronomers can probe much closer to the violent energy sources (probably black holes) present in extremely active galactic nuclei (AGN) such as quasars.

Traditional VLBI is limited in angular resolution by the Earth's diameter, which restricts the maximum baseline length available for ground-based telescopes. Therefore, the logical next step in the quest for increasing resolution is to put one or more radio telescopes in space to create interferometer baselines with a number of radio telescopes on the Earth. In the late 1980s, a 4.9-meter antenna aboard a satellite of the Tracking and Data Relay Satellite System (TDRSS) was used as a radio telescope in order to demonstrate the feasibility of space VLBI. Despite the many constraints on the observations and rather poor sensitivity of the space-based telescope, the TDRSS experiments detected more than 20 AGN at observing frequencies of 2.3 and 15 GHz.[4-7] Projected baseline lengths as long as 2.1 Earth diameters were sampled. 'These promising results demonstrated that (1) the technical problems of space VLBI are well understood and tractable; (2) many astronomical sources are strong and compact enough to be detectable on baselines greater than an Earth diameter; and (3) resolution considerably higher than that available from the Earth's surface yields important scientific results that cannot be achieved in any other way.

NASA currently is developing a program to achieve greatly improved angular resolution on astronomical objects through optical and infrared interferometry. Primary candidates for the first-generation space missions are the Orbiting Stellar Interferometer[8] and the Precision Optical Interferometer in Space.[9] These missions would largely investigate stars in our own Galaxy, both for important astrophysical results and in an effort to detect planets around other stars.[10] A future space VLBI mission would be complementary to the optical and infrared interferometers in two respects. First, the space VLBI mission would be most useful for investigating the nonthermal activity in extragalactic objects, a useful complement to the stellar (thermal) astrophysics that can be studied with the optical and infrared instruments. Second, it would enable a broadly based and coherent program of high-sensitivity and very high angular resolution space interferometry across a wide range of the electromagnetic spectrum.

This paper describes a candidate space VLBI mission named ARISE (Advanced Radio Interferometry between Space and Earth). ARISE recently was one of the missions selected for further study after a proposal in response to a NASA Research Announcement seeking "New Mission Concepts in Astrophysics." More details on this mission can be found elsewhere.[11,12] Here we concentrate on the requirements on the radio telescope that would be aboard ARISE, with emphasis on the great benefits that inflatable antenna technology would bring to such a mission.

Very Long Baseline Interferometry in the 1990s

VLBI is making significant advances in several areas in the 1990s.[13] The U.S. Very Long Baseline Array (VLBA) constructed by the National Radio Astronomy Observatory, has been operational since 1993.[14] The VLBA is an array of ten 25-m radio telescopes distributed around the United States in order to optimize the large aperture synthesized by all the radio interferometers. Included as part of the VLBA is a correlation facility that is capable of processing experiments with as many as 20 telescopes participating simultaneously. The European VLBI Network (EVN) is a consortium of nine institutes with 12 telescopes in Western Europe, with additional associated institutes and telescopes. The Joint institute for VLBI in Europe was formed in 1993 to provide scientific support for the EVN and to host a new 16-station correlation facility that is planned for completion in 1997. Southern Hemisphere VLBI also is being developed rapidly under the leadership of the Australia Telescope National Facility.[15]

The ground VLBI changes are being complemented by the first two dedicated space VLBI missions, scheduled for launch in the mid-to-late 1990s. Here, we concentrate on the aspects of these missions related to the main on-board radio telescopes. The first, the VLBI Space Observatory Programme (VSOP), is being developed by Japan's Institute of Space and Astronautical Science.[16,17] The spacecraft for VSOP, known also as MUSES-B, is scheduled for launch in September 1996. The planned 6.6-hour orbit will nave a perigee height of 1000 km and an apogee height of 22,000 km. A space radio telescope with an effective aperture of 8 meters will be used to make VLBI observations in conjunction with many ground telescopes, including those in the VLBA and the EVN. The large radio telescope is a Cassegrain system with a coaxial focal-plane feed supporting observations at 1.6, 5, and 22 GHz; the total mass of the antenna is approximately 250 kg.[18,19] The reflector is a deployable parabola composed of a thin wire mesh supported by a network of approximately 930 tension truss cables. Initial deployment of the antenna is actuated by six extensible masts) which also serve as rigid support structures for the cables and the entire antenna surface. The antenna is expected to have an r.m.s surface accuracy of approximately 0.5 mm (0.7-mm accuracy or better is required for excellent performance at 22 GH z). Aperture efficiencies ranging from 38% to 54% are expected at the three frequencies.

The second dedicated space VLBI mission, scheduled for launch in 1997 or 1998, is RadioAstron, led by Russia's Astro Space Center.[20] RadioAstron will be launched into a highly elliptical orbit with a perigee height of 4000 km and an apogee height of 77,000 km. RadioAstron is part of the Spektr series of three spacecraft, with the spacecraft bus being developed in Russia by the Lavochkin Association. The scientific payload aboard RadioAstron is a IO-meter space radio telescope, including all the associated equipment needed for doing VLBI. 'This telescope will perform at the same frequencies as VSOP, but with the additional observing frequency of 0.3 GHz. The radio telescope is a deployable parabola used in a prime-focus configuration, with the feeds and receivers located in a focal-plane instrument package.[21] The telescope, which has a mass of approximately 1200 kg, consists of 27 solid aluminum panels about 3.7 meters in length, attached to a central non-deployable section 3 meters in diameter. The panels are mounted on a graphite-epoxy backup structure. Their expected as-manufactured r.m s. surface precision is about 5 mm; ground measurements of the surface figure and adjustments of the attachment points will be used to improve the overall surface figure to the goal of 0.5 mm r.m s. Aperture efficiencies are expected to range from 30% to 50% at the different frequencies. Since the RadioAstron antenna is supportable in the Earth's gravitational field (unlike the VSOP antenna), tests of its performance as a ground-based VLBI telescope are possible, and preparation for those tests is well under way.

ARISE Mission Description

VSOP and RadioAstron will contribute important science as the first dedicated space VLBI satellites, However, with radio antennaa no more than 10 meters in diameter, and with uncooled receivers, the space telescopes have rather limited sensitivity. The space-ground interferometers will be a factor of about 5 more sensitive than the interferometers used in the TDRSS demonstrations, but are a similar factor less sensitive than an interferometer formed from two 25-m VLBA antennas. Therefore, only a limited set of the science goals for a space-ground VLBI array can be addressed with VSOP and RadioAstron. It is desirable that a second-generation mission such as ARISE be capable of studying the same classes of sources that can be studied from the ground, but with the additional angular resolution available using an orbiting element. Many more details of the ARISE mission and its scientific and technical requirements are given elsewhere.[12] However, the requirement to study the same types of sources accessible using ground VLBI leads to the critical design criterion for ARISE, namely that the space radio telescope must be at least as sensitive as the 25-m ground telescopes of the VLBA. In fact, since the sources to be observed will have lower correlated intensities on the longer space-ground baselines, it is highly desirable that the space element be somewhat more sensitive than a single VLBA ground radio telescope. Therefore, the radio telescope to be flown aboard ARISE should have a diameter of about 25-30 meters.

A second important criterion for the ARISE mission is good performance at high frequencies. Ground- based VLBI is currently done, albeit with somewhat limited sensitivity, at frequencies as high aa 86 GHz.[22] At such high frequencies, it is possible to study some aspects of energetic radio sources that are not accessible at observing frequencies of 22 GHz and below, regardless of the baseline length achievable. Therefore, it is extremely desirable that ARISE have high sensitivity at an observing frequency of 43 GHz, and also operate (perhaps with less sensitivity) at frequencies of 60 and 86 GHz. 'l'he 60-GHz observations would be done as a single radio telescope rather than as an interferometer element, in order to explore the complex of molecular oxygen lines that are expected to be very common in star-formation regions, but which cannot be observed from the ground due to absorption in the Earth's atmosphere. VLBI at 86 GHz would enable the investigation of the cores of AGN at a frequency where tile emission regions are optically thin, so that emission from the central power source is visible.

For a fixed integration time, the sensitivity of a radio telescope depends on three main parameters: (1) the effective area of the antenna; (2) the effective system temperature of the telescope; and (3) the square root of the bandwidth sampled (or the digital data rate). For a VLBI interferometer, the sensitivity depends on the same quantities, with the geometric mean of the areas and system ternperatures of the two telescopes replacing the values for an individual telescope. Table 1 provides a comparison of the sensitivities of different int,erferorneter baselines at the fairly common observing frequency of 22 GHz. (The sensitivity of a current VLBA system is defined to be unity, and hypothetical VLBA improvements for the year 2005 are assumed.) This table shows the tremendous sensitivity improvement desired for ARISE relative to the VSOP mission.

Table 1, 22-GHz Sensitivity on Baseline to a Single VLBA Antenna

Telescope Year	VSOP 1996	VLBA 1995	VLBA 2005	ARISE 2005
Diameter (m)	8	25	25	30
Efficiency	47%	52%	52%	60%
Sys. temp. (K)	200	85	60	10
Data rate (Mbps)	128	128	8192	8192
Sensitivity	0.2	≡ 1	12	40

ARISE would be a mission with a long enough lifetime to study the evolution of components in the cores of a number of radio sources and to explore a variety of classes of sources. Therefore, the proposed lifetime is 3–5 years. The orbit must be highly elliptical so that a wide range of baseline lengths (and corresponding angular resolutions) can be studied. The nominal perigee height is 5000 km, with an apogee height on the order of 50,000 km. A high orbital inclination, of approximately 60" relative to the Earth's equator, is desirable in order to provide the best possible VLBI imaging capability over the entire celestial sphere.

Inflatable Antennas for Space VLBI

In the 1980s and early 1990s, two other dedicated space VLBI missions were proposed. The first candidate was QUA SAT (for Q *UAsar SATellite*), studied both jointly and separately by NASA and the European Space Agency (ESA).[23] The second was the International VLBI Satellite (IVS), proposed to ESA.[24] The QUASAT concept relied on a new antenna technology under development by the Contraves company. This technology involved an antenna deployed by low-pressure inflation and then rigidized on orbit. The proposed antenna diameters were about 15 meters for QUA SAT and about 20 meters for IVS.

Many different antenna concepts might be possible for an advanced space VLBI mission .25 The antenna proposed for ARISE relies on a concept for an inflatable antenna structure that is under development by the L'Garde Corporation in California. It would be deployed and supported by means of inflatable struts and an inflatable torus that would rigidize on orbit. The surface of the inflatable antenna would be only a few microns thick, a factor of about 30 less than for the Contraves antenna. The inflatable antenna surface would not be rigidized on orbit. Instead, it would be maintained by a very low gas pressure of about 10--5 pounds per square inch, with a supply of gas replacing the slow leakage generated by the inevitable micrometeorite hits.

The L'Garde inflatable antenna concept is scheduled for test in the IN-STEP (IN-SPACE Technology Experiment) program, and is currently manifested for flight on the Space Transportation System in 1996.[26,27] In this test, a 14-m off-axis inflatable antenna surface will be deployed and inflated. The antenna surface will be illuminated with different patterns of light-emitting diodes, using different inflation pressures and thermal loads (Sun angles) for the inflatable structure. The resultant images of the light patterns will be used to deduce the various physical characteristics of the antenna surface, notably the curvature and the r.m.s. deviation from the desired shape. This dernonstration of deployability, as well as the measurement of surface accuracy, will be critical components in helping to demonstrate tile technical feasibility of the ARISE mission. One of the experiment goals is demonstration of a surface accuracy on the order of 1 millimeter, already close to the r.m.s. accuracy required for excellent performance at 22 GHz.

Science Requirements on Inflatable Antenna

Many of the design parameters for ARISE have been described previously .[12] In this section, we describe some specific requirements placed on the inflatable antenna by the scientific goals of ARISE.

Large Reflector Diameter

It was stated previously that the ARISE antenna should have a diameter of 25–30 meters in order to enable it to equal or exceed the sensitivity of ground-based VLBA telescopes. Since the orbiting telescope is free of the system temperature contributions from the Earth's surface and atmosphere, it will be possible for its system temperature to be lower than that for a ground antenna. This could enable the antenna diameter to be somewhat smaller than 25 meters and still achieve the stated sensitivity requirement. It is, however, probable that the antenna would need to be larger than the 14-m diameter inflatable system scheduled to be dernonstrat cd in orbit in 1996.

lIigh-Frequent.y Performance

The antenna surface accuracy should be good enough for excellent performance at frequencies up to 43 GIIz, with some capability remaining for frequencies ranging up to 86 GHz. Excellent performance requires an r.m.s. surface accuracy between 16 and 20 times better than the observing wavelength, amounting to a desired range of 0.35-0.44 mmf oruse at 43 GHz. This is a factor of 2-3 better than that expected for the IN-STEP experiment. However, it is believed that the dominant irregularities found in this experiment will be errors in the large scale curvature of the surface rather than small-scale irregularities. The challenge will be to see how much the surface accuracy can be improved by making simple engineering modifications, possibly including some capability for on-orbit antenna adjustment.

A surface accuracy of 0.4 mm would result in a telescope with a low aperture efficiency, in the range of 1OYO–2OYO, at 60 and 86 GHz. This is still quite adequate for making observations of the stronger VLBI sources at 86 GIIz and for mapping molecular oxygen at 60 GHz. An alternative would be to have a higher surface accuracy over some portion of the antenna and to use only that portion at the highest frequencies.

Open-Loop Pointing

The space radio telescope must have the capability of open-loop pointing to a particular celestial position with a pointing accuracy roughly equal to 1/10 of the beam width of the antenna. The most, stringent requirement for the ARISE antenna therefore is pointing of a 30-m antenna at 86 GHz, where the beam width would be about 25 arcseconds. hence, open-loop pointing capability on the order of 2–3 arcseconds is required. This will require very good modeling or calibration of thermal effects on the antenna, since its electrical axis is likely to change due to deformations caused by the Sun shining on it from the side.

Rapid Slew Capability

One very desirable capability for ARISE is the ability to slew the space radio telescope rapidly in order to repeatedly move back and forth between sources separated by distances of 0.5° to 2°. This enables the technique of phase referencing, which permits the detection of yet weaker radio sources. [28] A total cycle time of less than 15 seconds would be required to slew about 10 and settle to an accurate blind pointing position. Since phase referencing would be used only at frequencies up to 22 GHz, the requirement on the open-loop pointing is roughly 10 arcseconds rather than the more stringent value of 2–3 arcseconds needed for 86-GHz observations. The capability for this rapid, periodic slewing represents no more than about 1 0% of the science that would be done with A Ill SE, so it should not be allowed to drive either the antenna design or the spacecraft design to extremes.

Long Lifetime

The materials used in previous on-orbit applications of inflatable structures have had typical lifetime requirements of minutes, while the IN-STEP experiment will last for only 1–3 hours. However, A RISE must have a lifetime of 3–5 years. Therefore, the inflatable antenna must be robust for this several-year lifetime, during which it will pass through the Earth's charged-particle environment more than 1000 times. It also must not accumulate a high voltage that could discharge to the spacecraft and damage electronic components. The design parameters that provide the required antenna lifetime must not significantly degrade the radio-frequency performance, either by reducing the aperture efficiency or (as is more likely) increasing the effective system noise temperature.

Minimal Observing Constraints

A key feature of any space VLBI mission is the desire to minimize observing constraints, so that the synthesized large aperture can be "filled" as well as possible by interferometry observations. In addition, it is desirable to have the capability of observing particular sources for as large a fraction of the year as possible. Some of the major antenna-related constraints that exist for the VSOP and RadioAstron missions must be reduced, including the following: (1) the solar panels must not be shadowed by the large reflector, so that the radio telescope can observe much closer to the Sun than the 60°-70° minimum Sun angle required for VSOP and RadioAstron; (2) communication with the Earth must not be restricted because of the large reflector occulting the Earth as seen by the telemetry antenna(s); and (3) adequate solar power must be available even if the solar panels are not orthogonal to the Sun, so that the pointing direction of the radio telescope need not be highly constrained by solar-power considerations. It currently is believed that an off-axis reflector segment, with the spacecraft at the focal point, best satisfies these constraints.

Additional Requirements on inflatable Antenna

This section describes some requirements placed on the inflatable antenna by the engineering and programmatic aspects of the ARISE mission.

Low Cost

The ARISE mission is possible only if the large radio telescope does not drive the cost of the mission to an unreasonable value. A mechanical deployable antenna with a diameter of 25 to 30 meters is likely to cost $500 million to $1 billion. In general, the inflatable antenna concepts arc considerably less expensive. For example, the total IN-STEP experiment cost is less than $10 million, with only part of that money being spent on the inflatable antenna structure. An extremely low cost also would make it possible to orbit more than one spacecraft simultaneously, which would greatly improve the capability to make very high quality images at the highest resolution.

High Deployment Reliability

The deployment and inflation mechanisms must be as simple as possible so that ARISE can be successfully implemented. There may be a tradeoff to be made between simplicity of design and high-frequency surface accuracy. Given the recent experience with Galileo, it also will be very difficult for NASA to approve a mission unless there has been a clear demonstration of deployment reliability, which should be provided by the IN-STEP experiment.

Compact Packaging

The stowed 25–30-m ARISE antenna must be packaged in a relatively small volume to fit within a launch vehicle shroud. in at least two of the three orthogonal axes, the package diameter must be less than 3.5 meters to fit inside an Atlas launch vehicle, and less than 3 meters to fit inside a Delta fairing. The compact packaging must be achieved without sacrificing deployment reliability. For the IN-STEP experiment, the total size of the package for the 14-m deployable antenna surface fits within both these constraints.

Low Mass

Low antenna mass is desirable for several reasons. A lower mass enables a much larger selection of orbits for a given launch vehicle, or a smaller (and less costly) launch vehicle for a given desired orbit. In particular, a lower mass will make it easier to reach the high-inclination orbit desirable from a scientific point of view. A low antenna mass also will require less power and torque to slew the antenna using actuators located at the main body of the spacecraft, which would be at the antenna focal point, about 10–15 meters from the antenna surface. A worthwhile goal would be to keep the total mass of the inflatable antenna (including struts and torus) less than the 250 kg of the $-m VSOP antenna. This seems feasible since the mass of tbe 14-m inflatable structure of the IN-STEP experiment is less than 100 kg.

Summary

Inflatable antenna technologies provide a possible breakthrough for a future space VLB1 mission. An IN-STEP flight experiment in 1996 is expected to be an important demonstration of some of the antenna technology necessary for the proposed ARISE mission. This paper has described some of the scientific, engineering, and programmatic requirements that will present challenges to the design of an antenna for ARISE and to its integration with the remainder of the scientific payload and spacecraft. If these challenges can be successfully met, a scientifically exciting radio interferometry mission with a large orbiting antenna should be both technically viable and quite affordable.

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